Fully Electric (Battery/Fuel Cell) powered Submarine

And its performance compared to other submarine designs

Sven Los

Nevesbu B.V., Alblasserdam, The Netherlands

Abstract

Conventional submarines use a diesel-electric power plant. However, this might change in the nearby future. The ongoing research of civil industries into alternative power plant solutions, such as high capacity batteries and fuel cells, leads to technical improvements. This might make alternative power plants in submarines feasible in the nearby future. On last year's UDT, a totally battery powered concept the E-MORAY was presented [01]. This paper presents a full electric battery/fuel cell powered submarine design; the H_2MORAY. This design has a power plant consisting out of high capacity lithium batteries and polymer electrolyte membrane fuel cells. Hydrogen storage will be achieved by means of high pressure bottles outside the pressure hull containing pure hydrogen. The H_2MORAY will be able to reach ranges up to 2920 nautical miles and an endurance of 42 days, without needing to surface. This enables the design to perform local to medium range missions with a high level of covertness. The H_2MORAY has improved operational capabilities compared to the E-MORAY, which is able to reach a range of 1950 nautical miles and an endurance of 24 days. However, this is at the cost of higher design complexity. Compared to conventional diesel-electric submarines, the range and endurance of designs with an alternative power plant is still significantly less. However, with the expected improvements in technology the potential of totally battery powered and fuel/battery powered submarines is expected to increase in the nearby future. This will make such designs realistic alternatives for the conventional diesel-electric submarine.

1. Introduction

The submarine propulsion plant is a significant factor for both the submarine performance and the overall design balances. Currently, non-nuclear submarines still use conventional diesel-electric propulsion plants. However, this might change in the nearby future.

On last year’s UDT, Nevesbu presented a total battery powered submarine design [01]. This concept clearly showed the potential of alternative propulsion solutions for non-nuclear submarines. Already significant ranges and endurances can be achieved and these are expected to improve with the expected improvement in technology. Furthermore, advantages like air independent propulsion, improved stealth, reduction in design complexity, reduction in maintenance, improvement in availability and a reduction in crew size can be achieved when diesel-generators are removed from submarine designs.

An interesting design option is combining a fuel cell system with batteries creating a fully electric (battery/fuel cell) powered submarine design. In recent years, Nevesbu developed a propulsion plant model which enables the design and optimization of submarine propulsion plants based on first principles [02][03]. Simulations show that for long submerged missions, a combination of lithium batteries and fuel cells have the lowest weight and volume requirements [03]. Therefore, it is expected that a fully electric (battery/fuel cell) powered submarine will currently achieve a higher range and endurance than a totally battery powered submarine. However, this will be at the cost of a higher design complexity.

As mentioned before, the submarine propulsion plant is a significant factor for both the submarine performance and the overall design balances. The effect of a full electric battery/fuel cell power plant on a submarines design is currently unknown. A goal of this study is to investigate this impact and to come up with a balanced design. This design will be used to assess the performance of such a fully electric submarine with respect to achievable range and endurance and to compare this with other submarine designs. Furthermore, the different concepts will be compared on design considerations as: signatures, complexity safety, maintainability and operational performance.

2. Power plant design

2.1 Power plant layout

In this study a power plant will be applied as is shown in Figure 1. The fuel cells will be sized to provide sufficient power to achieve transit speeds. The battery pack will be sized to provide energy storage capacity for high speed bursts. After high speed burst, the fuel cells can be used to recharge the batteries at a lower submarine speed.

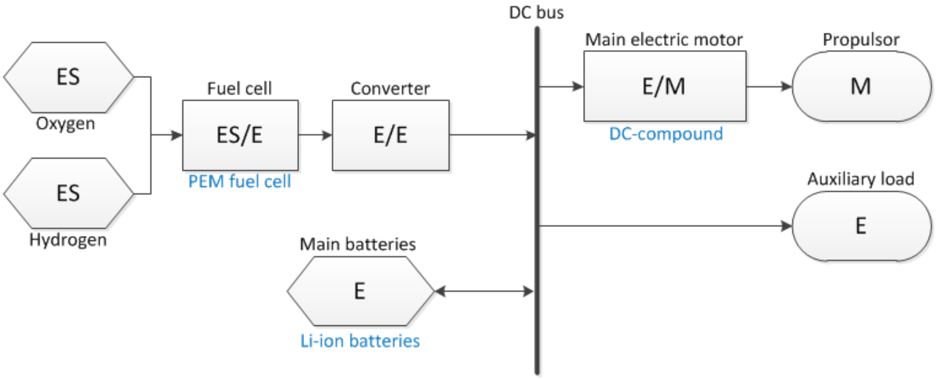

Figure 1: High level energy flow diagram of a fully electric (battery/fuel cell) power plant

As fuel cell system, a polymer electrolyte membrane fuel cell (PEMFC) is used. PEMFC is chosen because it has high efficiency and power density, it is silent, free of vibrations and the technology is well developed. Furthermore, this system is already applied in multiple submarine designs.

Lithium-ion batteries are used as main batteries. It is mainly intended to use the main batteries to achieve high submarine speeds. Lithium batteries have a high energy storage capacity and perform well at high discharge rates, which makes them suitable for this application. Furthermore, the maturity and safety of lithium batteries have significantly improved in the last years. In this study, lithium batteries with a LTO coated NMC chemistry are used [04].

The range and endurance of fully electric submarines, with the power plant of Figure 1, will be dependent of the oxygen and hydrogen storage capacity. As oxygen storage, LOX tanks will be used. This is an effective way to storage oxygen and is already applied in multiple submarines. As hydrogen storage solution, the storage of hydrogen will be used. Reformation of hydrogen is not chosen mainly due to high system complexity and the impact on the submarines signatures. The applied hydrogen storage solution will be described in more detail in the next paragraph.

2.2 Hydrogen storage

There are multiple ways to store hydrogen. The storage solutions can be rated by mass storage efficiency and volume storage density. Figure 2 gives an overview of the different hydrogen storage techniques.

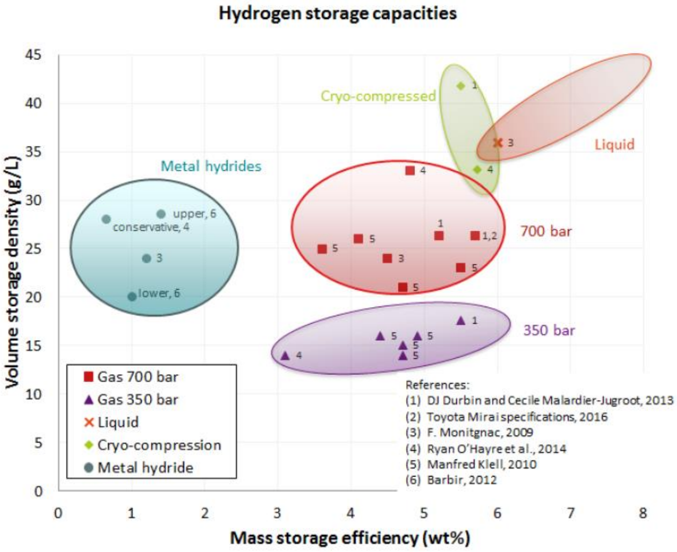

Figure 2: Comparison of different hydrogen storage techniques [07]

Cryo-compressed and liquid hydrogen storage is most efficient with respect to mass and volume, as can be seen in Figure 2. Liquid hydrogen storage is not feasible, since boil-off losses are inevitable and at least 35% of the fuels energy needs to be used to keep it liquefied. Cryo-compressed hydrogen storage is an interesting upcoming technology, but is not sufficiently developed yet.

In the type 212 and type 214 submarines, hydrogen storage in metal hydrides is used. Many types of metal hydrides are possible. In general, metal hydrides have a relatively good volumetric storage density but have also low mass storage efficiency. Furthermore, refuelling of metal hydrides is complicated.

In the automotive industry, high pressure storage of hydrogen is the technology of choice. Hydrogen is stored in carbon fibre reinforce plastic (CFRP) bottles up to a pressure of 700 bar. These CFRP bottles are designed with built on pressure regulators, which ensures lower pressure after the bottles. High pressure storage has high volumetric and mass storage efficiency. Furthermore, it can be easily refilled and the system is commercially available. Therefore, high pressure hydrogen storage is chosen as hydrogen storage technology for this study.

High pressure hydrogen storage introduces a safety risk. A leakage of 700 bars of hydrogen within the pressure hull will instantly lead to high hydrogen concentrations in the submarines atmosphere, resulting in severe safety risks. Therefore, the hydrogen storage bottles will be applied outside the pressure hull. The hydrogen pressure will be reduced to the PEMFC operation pressure (approx. 5 bar) before entering the pressure hull. A principle diagram of the hydrogen storage solution is shown in Figure 3.

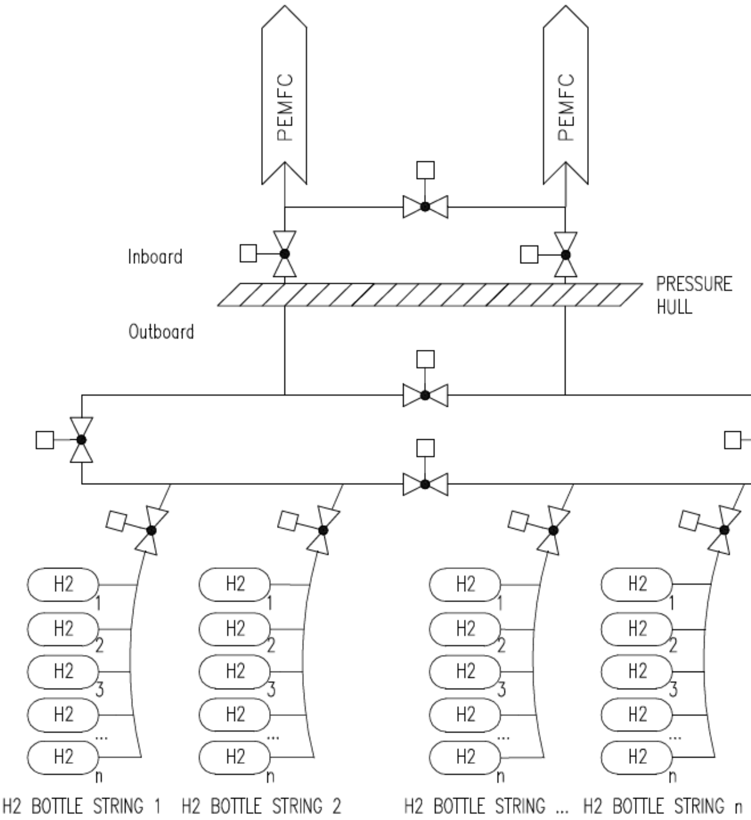

Figure 3: Principle diagram of string based hydrogen storage

This string based hydrogen storage solution will provide a high level of redundancy and safety. When a single bottle is damaged or if the pressure regulator malfunctions, a string can be disconnected resulting only in a slightly reduced capacity. Furthermore, a leakage will not pose a safety risks since hydrogen is leaked outside the pressure hull. Redundancy can be increased if required by addition of crossovers.

3. Fully electric (battery/fuel cell) powered submarine

A concept design of a fully electric (battery/fuel cell) powered submarine is made to assess the impact on the design and operational/missions capabilities. The 1800 tons diesel-electric submarine MORAY 1800 is used as reference for this study [06]. Which is the same reference design used for the total battery powered submarine design of 1800 tons displacement, as presented on last year's UDT [01]. The submarines displacement and design requirements (as for example payload and maximum achievable speed) will be kept constant to enable a fair comparison between the three designs.

3.1 The H_2MORAY Concept

The H_2MORAY design is optimized for hydrogen and oxygen storage capacity. A complete double hull design is created to enable the storage of hydrogen bottles outside the pressure hull. The arrangement of the hydrogen bottles can be seen in Figure 4. The hydrogen bottle size is based on commercially available high pressure hydrogen bottles. The bottles and piping will connected to the pressure hull framing. The valves will be accessible from the superstructure. Removable panels will be applied to ensure accessibility during maintenance periods.

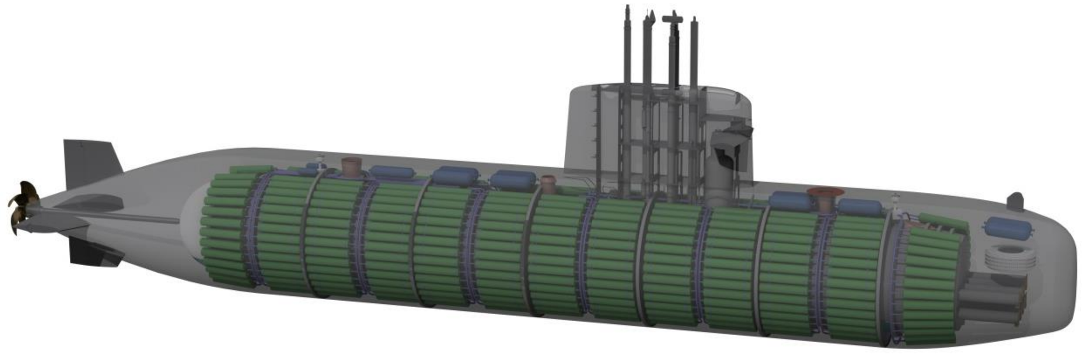

Figure 4: Hydrogen bottles arrangement of the H_2MORAY concept

The internal arrangement is optimized for large scale LOX storage, the required compensation capacity and safety. The H_2MORAY is shown in Figure 5. The fuel cells are placed in an air tight compartment after the main electro motor room. This compartment will be normally unmanned and will not be connected to the rest of the submarines atmosphere. This will ensure that if a hydrogen leakage occurs, it will be contained in one closed compartment. In the H_2MORAY two large LOX tanks are integrated. The LOX tanks will be surrounded with LOX compensation tanks, which enable the compensation of lox without trim disturbances. The main characteristics of the H_2MORAY are shown in Table 1.

The submarine dimensions are changed with respect to the MORAY 1800 design. The large amount of hydrogen bottles outside the pressure hull add to the displacement of the submarine. The pressure length and pressure hull diameter is decreased to compensate for this and keep displacement constant (to enable a fair comparison in chapter 4). After the design process, it is clear that the design of a fully electric (battery/fuel cell) powered submarine is volume critical. This is mainly the result of the required LOX storage capacity. First of all, the LOX tanks have large volume requirements and are inefficient due to the cylindrical shape. Secondly, separate LOX compensation tanks are required to compensate the weight of the LOX. The LOX storage capacity is therefore expected to be the limiting design factor when the hydrogen storage efficiency increases. In the H_2MORAY lead ballast of 10% of the submerged displacement is required.

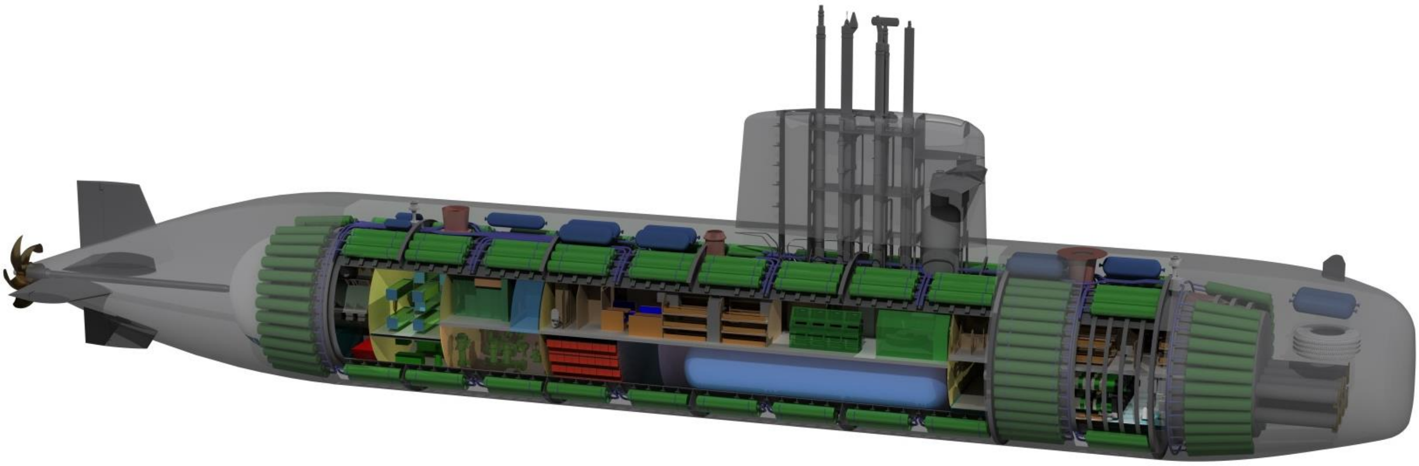

Figure 5: The H_2MORAY concept

Table 1: Main characteristics total battery powered concept design

Dimensions	Length over all	64.4	m
	Pressure hull diameter	6.4	m
Displacement	Surfaced	1700	ton
	Submerged	1900	ton
Diving depth	Max. operational	300	m
Combat	Launching tubes	6	-
	weapons	20	-
Speed	Max for one hour	20	kn
	Burst	21.5	kn
Batteries	Installed capacity	7.4	MWh
Fuel cell	Installed fuel cell power	800	kW
	Number of fuel cells	8	-
Hydrogen	Storage capacity	7.7	ton
	Number of high pressure bottles	382	
LOX	Storage capacity	68	ton
Autonomy	Range @ 5 kn & nominal aux.	2920	Nm
	Submerged endurance @ 2 kn	42	days
Accommodations	Crew & trainees	34+4	-

3.2 Operational capabilities

The design of the H_2MORAY is used to assess the operational capabilities of battery/fuel cell powered submarines. Use is made of submarine propulsion plant models developed by Nevesbu [02][03].

The power plant of the H_2MORAY is completely air independent. Therefore, the submerged range and endurance are equal to the total range and endurance of the design. In Figure 6, the range and endurance of the H_2MORAY concept is shown. In the graphs, two auxiliary load conditions are shown to indicate the sensitivity of the auxiliary load in the lower speed regions. The auxiliary load conditions correspond with the nominal auxiliary load (maximum during normal operation) and minimal auxiliary load (minimum during normal operation).

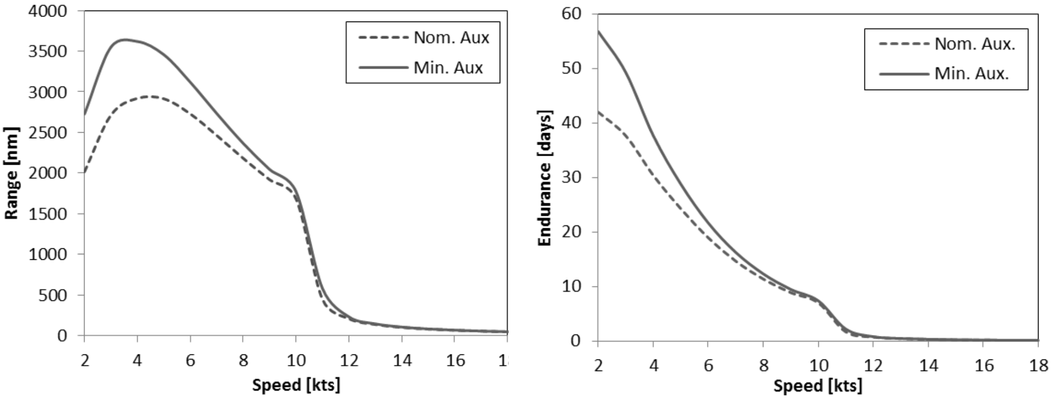

Figure 6: Range and endurance of H_2MORAY concept

Figure 6 shows that the H_2MORAY will be able to reach a range of more than 3000 nautical miles and an endurance of more than 42 days. The power limit of the fuel cells is clearly visible in Figure 6 as well. From a speed of 10 knots, the power output of the fuel cells is too low and battery pack will be required to provide sufficient power to reach the higher speed regions. Therefore, the range and endurance on speeds higher than 10 knots is dependent on the energy storage capacity of the batteries. The endurance at high speeds is better visible in Figure 7.

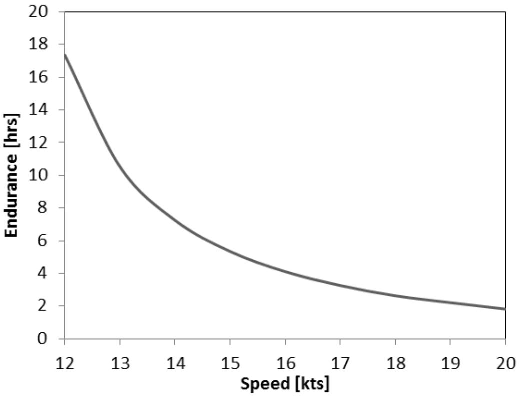

Figure 7: Endurance of H_2MORAY concept in higher speed regions

The H_2MORAY has the capability to charge its batteries after a period of high speed sailing. At slower speeds, the overcapacity of the fuel cells can be used to charge the submarines batteries. The battery charge time is therefore dependent on the submarines speed. In Figure 8 the battery charge time of the H_2MORAY is shown for battery charging from a depth of discharge (DoD) of 0.8 to a DoD of 0.2 and a nominal auxiliary load.

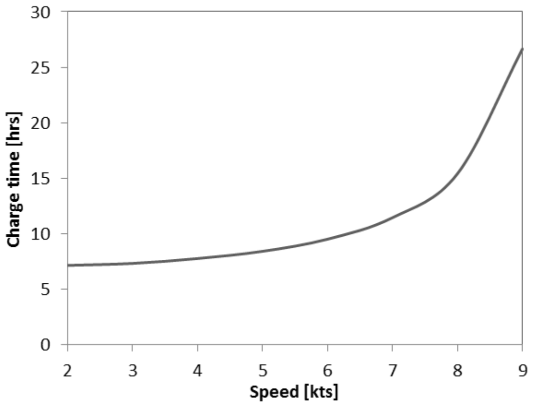

Figure 8: Battery charge time from DoD of 0.8 to a DoD of 0.2

3.3 Mission capabilities

The operational capability study shows that the H_2MORAY can reach an endurance of up to a month and a range of up to 3000 nautical miles during normal operation. These operational capabilities make the H_2MORAY suitable for local to medium range missions. In Figure 9, a four week round trip of 2500 nautical miles is shown to give an indication of the mission capabilities. During such a round trip, multiple high speed manoeuvres are possible. Furthermore, the complete roundtrip can be performed without surfacing once. A round trip, as shown in Figure 9, is not a realistic mission. However, it does clearly give an indication of the capabilities of the H_2MORAY.

The H_2MORAY has good stealth characteristics. The propulsion is air-independed and silent due to the use of fuel cells and batteries. This enables to submarine to perform complete missions covert. These characteristics combined with the operational capabilities make the H_2MORAY suitable to perform missions as sea control/denial, intelligence gathering and Special Forces deployment in local to medium range mission areas. Such a design would therefore be suitable to perform coastal defence missions.

It is not yet feasible to perform ocean going expeditionary ocean going missions with a full electric battery full cell power submarine. The range and endurance are currently too limited. Furthermore, fleet escorts are not feasible due to the limited endurance in the higher speed regions.

Figure 9: Indication of mission capability of H_2MORAY

4. Comparison with diesel-electric and totally battery powered submarine

In the last years, Nevesbu performed multiple studies into the topic of submarine propulsion plant optimisation and into alternative propulsion plant solutions and designs with future potential [01][02][03]. In chapter a comparison, a comparison will be made between a diesel-electric submarine, a totally battery powered submarine and a battery/fuel cell powered submarine design.

4.1 Overview of the three MORAY designs

As base line, the conventional diesel-electric submarine the MORAY 1800 is used [06]. Both the totally battery powered design (the E-MORAY [01]) and the battery/fuel cell powered submarine (H_2MORAY) are based on this design. All three designs have the same design requirements as; environmental conditions, payload, crew size and maximum speed. Furthermore, the displacement is kept constant to enable a fair comparison between the designs. The only difference between the designs is the power plant. An overview of the main characteristics of the three designs is shown below.

Table 2: Overview of the three MORAY designs

		MORAY 1800 [06]	E-MORAY [01]	H_2MORAY	
Dimensions	Length	66.5	66.5	64.4	m
	Pressure hull diameter	6.5	6.5	6.4	m
Displacement	Submerged	1900	1900	1900	ton
Diving depth	Max. operational	300	300	300	m
Combat	Launching tubes	6	6	6	-
	weapons	20	20	20	-
Speed	Max for one hour	20	20	20	kn
Accommodations	Crew & trainees	38	38	38	-
Machinery	MEM	4360	4360	4650	kW
	Installed DG power	2940	-	-	kW
Batteries	Installed capacity	12.3	88.5	7.4	MWh
Fuel cell	Installed fuel cell power	-	-	800	kW
Autonomy @	Submerged endurance @ 2 kn	3	24	42	days
nominal aux	Maximum achievable range	10900	1950	2920	nm

4.2 Operational capabilities

The three designs mainly distinct themselves based on operational capabilities. A comparison between the submerged range and endurance is shown in Figure 10. The submerged range and endurance of the MORAY 1800 is limited, due to the diesel-electric propulsion plant and the absence of an AIP system. Both the E-MORAY and H_2MORAY have significant improved submerged capabilities. The H_2MORAY has best submerged capabilities in the low speed region, which are 25-75% better than the E-MORAY (depending on the speed).

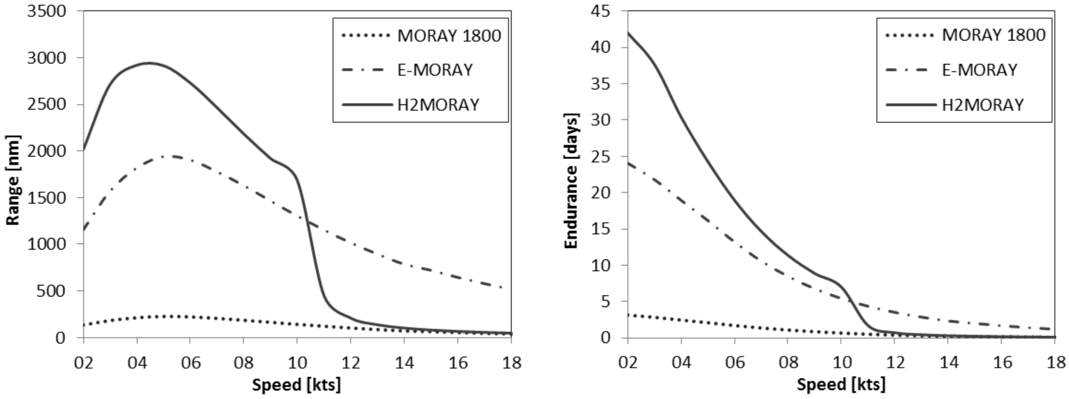

Figure 10: Comparison of submerged range and submerged endurance of three submarine designs

Looking at the total range of the three designs in Figure 11, it is clear that there is still a big gap between the diesel-electric MORAY 1800 and the E-MORAY and H_2MORAY. The total range of MORAY 1800 is 5.5 times higher than the E-MORAY and 3.7 times higher than the H_2MORAY. The difference is caused by the higher specific energy of fuel oil, the fact that fuel oil is easy to store and compensate in the same tanks and that atmospheric air is used for the operation of diesel-generators.

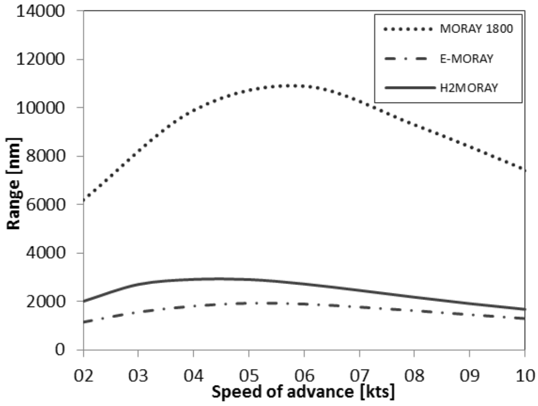

Figure 11: Comparison of total range of three submarine designs

4.3 Design considerations

The difference in operational capabilities is clearly visible in the previous paragraph. However, there are multiple other aspects which are influenced by the power plant choice.

A submarines strength is its covertness. The power plant of a submarine is a main contributor to the submarines signatures. In a diesel-electric submarine, the need of snorting is the biggest contributor to the submarines signatures. During snorting, the submarine can be spotted visually and with radars. Furthermore, they will have a significant noise- and heat signature during snorting. Both the E-MORAY and the H_2MORAY have a significantly improved covertness due to the air-independent propulsion and a reduction in signatures. The E-MORAY performance slightly better than the H_2MORAY, since the fuel cells require cooling constant cooling which effects the signatures slightly.

Another design consideration is complexity. The three different concepts have complete different level of complexity. The design complexity has an indirect effect on many other aspects. A high level of design complexity often results a long design and production time. Furthermore, it has an influence on the operability, maintainability and availability of the submarine. A complex design requires a high level of knowledge from the crew and will increase the workload on-board the submarine. Furthermore, it can results in a higher maintenance workload and downtime which reduces the availability of the design. Lastly, the design complexity directly influences the complete life cycle costs of the submarine. Looking at the difference in design complexity, it can be concluded that the E-MORAY is the least complex design. The E-MORAY has significantly less equipment, piping and pressure hull penetrations than a diesel-electric submarine. The H_2MORAY can be considered equivalent complex as a diesel-electric submarine. The H_2MORAY requires a large amount of tanks, piping, piping connections and automatically controlled valves (which also need to be of special material to deal with the metal degradation process due to interaction with hydrogen) and an increase in pressure hull penetrations. This makes the outer pressure hull hydrogen storage system complex.

Safety is very important in submarine design. The power plant often has a big influence on the platform safety. In a conventional diesel-electric submarine, the biggest safety risks are originating from the diesel-generators and lead-acid batteries. The diesel-generators impose the risks of fire, exhaust leakages, atmosphere pressure drops and water leakages via the snorkel installation. The lead-acid batteries produce hydrogen, which imposes the risks of fire and explosions. In the H_2MORAY the biggest risk is originating from hydrogen and LOX. The storage outside the pressure hull reduces the risks of high pressure hydrogen storage. However, only small hydrogen leakage imposes already a severe safety risks due to the high flammability at low mixture percentage. Furthermore, the large scale LOX storage inside the pressure hull has safety risks with respect to fire, toxicity at high exposure rates and the low storage temperature. The biggest safety risk of the power plant of the E-MORAY is originating from the lithium batteries. The risk of lithium batteries is fire caused by thermal runaway. In a big battery pack, a single cell failure can result in propagation through the complete battery pack. However, this risk is already significantly reduced for newer generations of lithium batteries [04].

4.4 Future outlook

Both fuel cells and batteries are considered the solution to achieve emission free transport in multiple civil industries, with the automotive industry as clearest example. Therefore, significant amount of research is performed on topics of high capacity batteries, fuel cells and hydrogen storage. It is therefore expected that performance of both the E-MORAY as the H_2MORAY will improve in the nearby future.

It is difficult to assess how soon and how big the impact of technical developments will be. A rough estimation is made, based on multiple public sources (e.g. [08][09]), to assess the impact of the expected technical improvements on both the operational capabilities of the E-MORAY and H_2MORAY concept. This estimation is shown in Figure 12 and Figure 13.

For Battery powered submarines, such as the E-MORAY concept, improvements in battery technology will directly lead to improved operational capabilities. If the most positive prospects will become reality, all electric (battery powered) submarines will be able to reach ranges up to 7000 nautical miles. Totally battery powered submarines will be a very realistic design options when these prospects become only partly reality.

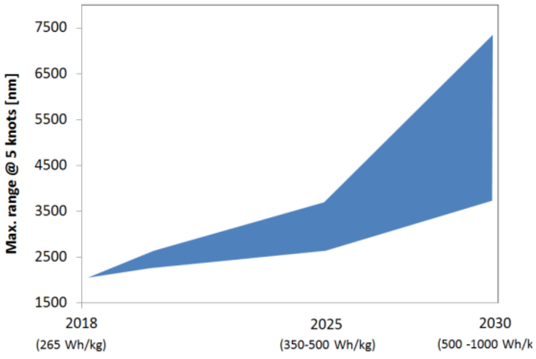

Figure 12: Potential of expected improvement of battery capacity on the maximum range of the E-MORAY

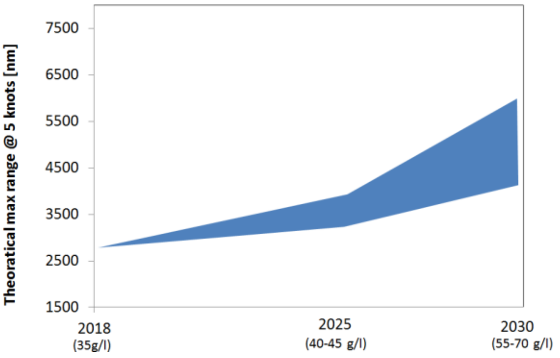

Figure 13: Potential of expected improvement of hydrogen storage density on the maximum range of the H_2MORAY

For fuel-cell powered submarines, the prospects are current slightly less; up to 5500 nautical miles. However, there are new developments such as solid state hydrogen storage which are not included in this comparison. These might lead to significantly improved prospects in the future. There is one important factor to take into account when looking at the prospects of fuel-cell power submarine; the required oxygen storage capacity. An increase in hydrogen storage capacity will require an increase in oxygen storage and oxygen compensation capacity as well. In the H_2MORAY concept, the required oxygen storage and compensation capacity are already limiting design factors. Furthermore, improvement of oxygen storage is not a research topic of civil industries. Therefore, no significant improvements in oxygen storage efficiency are expected. Oxygen storage is expected to be the limiting factor in the development of fuel cell powered submarines.

4.5 Power plant selection

With the expected development in technology, the feasibility and capabilities of alternative power plant solutions for submarines are increasing. The importance of a well-considered power plant choice will therefore continue to increase in the nearby future. The choice for a propulsion plant solution should be based on a good trade-off of all technical, operational and financial aspects of the power plant.

An important input for the power plant selection is a clear concept of operations. For example, a diesel-electric submarine (with AIP) is a logical choice when an expeditionary submarine is required by a navy. However, a battery powered or fuel cell/battery powered submarine can provide multiple advantages when a submarine is required for coastal defence and local to medium range missions. Furthermore, for the choice between a battery powered and fuel cell/battery powered submarine a trade-off needs to be made between operational capabilities and design complexity/safety.

5. Conclusion

The presented fuel cell/battery powered H_2MORAY concept will be able reach ranges up to 2920 nautical miles and an endurance of 42 days, without the need to surface. This enables the design to perform local to medium range mission with a high level of covertness.

A comparison with other submarines designs (conventional diesel-electric and totally battery powered) show that the H_2MORAY will have the highest submerged range and endurance. However, the total range and endurance a diesel-electric submarine will still remain significantly higher. Furthermore, a totally battery powered submarine will perform better with respect to design complexity.

This research clearly shows the potential of non-nuclear submarines with alternative propulsion plant solutions. This potential is expected to increase due to the expected commercially driven improvements in energy storage capacity of batteries and the storage capacity of hydrogen. This makes both totally battery powered and battery/fuel cell powered submarines realistic design options. The choice between the two shall be strongly influenced by the development speed of battery technology and hydrogen storage solutions. If totally battery powered submarines will be able to achieve the same operational capabilities as fuel cell powered submarines, they will be favourable due to the lower design complexity.

Another conclusion which can be made is that commercially driven developments will impact submarine design considerations. Whereas in the past developments were mainly military driven. Therefore, it is of importance to analyse commercially driven developments to be able to evaluate their potential for the undersea defence industry.

References

[01] Los, S. & Schiks, W. (2018). Total battery powered submarine design, a new way of thinking, *Undersea Defence Technology 2018*

[02] Boogaart, R. & Rietveld, L. (2017). Optimization of a propulsion plant for a submarine based on first principles, *Undersea Defence Technology 2017*

[03] Boogaart, R., Hacken, M., Visser, K. & de Vos, P. (2018). Submarine Propulsion Plant Design using Mean Value First Principle models, *Undersea Defence Technology 2018*

[04] Chong, C.Y., (2018). Lithium-ion Technology for Submarine Main Battery, *Undersea Defence Technology 2018*

[05] Gunter Sattler, (2000). Fuel cells going on-board, *Journal of power sources 86(1):61-67*

[06] Prince, C.A. & Stapersma, D., (1990) AIP for ocean going submarines, *U-90 International Conference on Submarine Systems Stockholm*

[07] Hacken, M. (2017) Optimization of a submarine propulsion system by implementing a PEM fuel cell and a PMSM in a first principle model, *Master Thesis Technical University of Delft*

[08] European Association for Storage of Energy, European Energy Research Alliance, (2013) Recommendations for a European Energy Storage Technology Development Roadmap towards 2030

[09] International Hydrogen Fuel Cell Association, Society of Automotive Engineers of China (2018), Technology Roadmap for Energy Saving and New Energy Vehicles